Testing Fundamental Gravity via Laser Ranging to Phobos

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Abstract

Phobos Laser Ranging (PLR) is a concept for a space mission designed to advance tests of relativistic gravity in the solar system. PLR's primary objective is to measure the curvature of space around the Sun, represented by the PPN Eddington parameter γ, with an accuracy of two parts in 10^7. Other mission objectives include measurements of the time-rate-of-change of the gravitational constant, G and of the gravitational inverse square law at 1.5 AU distances—with up to two orders-of-magnitude improvement for each. A transponder on Phobos sending 0.25 mJ, 10 ps pulses at 1 kHz, and receiving asynchronous 1 kHz pulses from earth via a 12 cm aperture will permit worst-case links exceeding a photon per second. A total measurement precision of 50 ps demands a few hundred photons to average to 1 mm (3.3 ps) range precision. Existing SLR facilities—with appropriate augmentation—will be able to participate in PLR ranging. Since the Phobos orbit period is about 8 hours, each observatory is guaranteed visibility of the Phobos instrument every Earth day.

1. Introduction

Laser ranging from the Earth to passive targets on the lunar surface routinely operates at centimeter level accuracy (Williams et al., 2009). Millimeter-level accuracy lunar laser ranging (LLR) data has been achieved by the Apache-Point Observatory Lunar Laser-ranging Operation (APOLLO) (Murphy et al., 2008). Over the years, LLR has benefited from a number of improvements both in observing technology and data modeling. Today LLR is a primary technique to perform high-accuracy tests of relativistic gravity including tests of the Equivalence Principle (EP), of a time-variability in the gravitational constant, and of the inverse-square law of gravity.

The PLR mission described here would provide tests of relativistic gravity in the solar system to an unprecedented precision. It would test the weak-gravity-and-small-speed regime of the cosmologically motivated theories that explain the small acceleration rate of the Universe (a.k.a. dark energy) via modification of gravity at cosmological scales. PLR would search for a cosmologically-evolved scalar field that is predicted by modern theories of quantum gravity and cosmology, and also by superstring and brane-world models. The Eddington parameter, γ, whose value in general relativity is unity, is the most fundamental parameter in that ½(1−γ) is a measure, for example, of the fractional strength of the scalar gravity interaction in scalar-tensor theories of gravity (Turyshev, 2009). Specifically, the quantity ½(1−γ) defines corrections to the spacetime around massive bodies. To

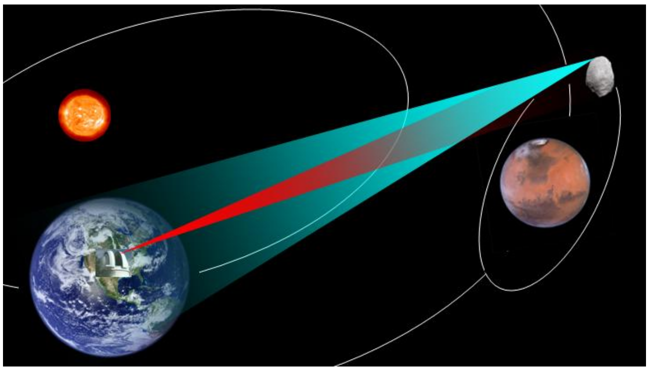

Figure 1. Concept of a laser transponder link between an observatory on Earth and a laser terminal on Phobos.

date, the most precise value for this parameter, $\gamma-1=(2.1\pm2.3)\times10^{-5}$, was obtained using microwave tracking to the Cassini spacecraft (Bertotti et al., 2003) during a solar conjunction experiment. This accuracy approaches the region where multiple tensor-scalar gravity models, consistent with recent cosmological observations (Spergel et al., 2007), predict a lower bound for the present value of this parameter at the level of $(1-\gamma) \sim 10^{-6}$–10^{-7}. Therefore, improving the measurement of γ would provide crucial information to separate modern scalar-tensor theories of gravity from general relativity, probe possible ways for gravity quantization, and test modern theories of cosmological evolution (Turyshev, 2009; Turyshev et al., 2009). With an accuracy of two parts in ten million anticipated from PLR measuring the Eddington parameter γ, this mission could discover a violation or extension of general relativity, and/or reveal the presence of any additional long range interaction.

The PLR experiment will build on the success of LLR, but will break the passive lunar paradigm (strong signal attenuation due to $1/r^4$ energy transfer) and extend the effectiveness of this technique to interplanetary scales (Fig. 1). At interplanetary distances, active techniques are required to achieve good signal strength (a benefit of $1/r^2$ energy transfer). The development of active laser techniques would extend the accuracies characteristic of passive laser ranging to interplanetary distances. Technology is available to conduct such measurements, achieving single-photon time resolution measured in tens of picoseconds (ps). One millimeter of range corresponds to 3.3 ps; millimeter range precision can be statistically achieved with a few hundred photons in both uplink/downlink directions. For comparison, several-meter accuracies have been achieved for radio tracking at Mars. Interplanetary laser ranging has been demonstrated with the MESSENGER spacecraft (Smith et al., 2006).

Building on our experience with APOLLO’s design, construction and operations, LLR data analysis, and optical communications technology development, we propose a medium-class mission to Phobos that would be deployed on the surface of Mars’ largest satellite and operate a pulsed laser transponder (time-of-flight) capable of achieving mm-class accuracies in ranging between Earth and Phobos. The resulting PLR experiment would initiate investigations in several science areas, focusing primarily on gravitational astrophysics over a nominal 3-year science mission.

2 Technical Overview of PLR Mission and Experiment

2.1 Mission Description

The Phobos Laser Ranging mission is based on deploying a laser ranging transponder instrument capable of supporting measurements of distances to Earth with 1 mm accuracy given daily hour-long tracking passes. Phobos was selected as the target body as being far enough from Earth to fully sample the solar system gravity field with relatively low cost of delivery while being free of an atmosphere which would induce variable refraction and scatter sunlight. Phobos rotates synchronously while orbiting about Mars with an 8 hour period. The anti-Mars point was selected as being easiest to land on, have full view of Earth three times per Earth day, and have good sunlight illumination for solar panels.

The PLR spacecraft configuration is fairly simple. The box-like main structure would have four legs rigidly attached for landing on Phobos (Fig. 2). The spacecraft easily fits within the fairing of an Atlas V-401 launch vehicle, the smallest Mars-capable vehicle under NASA contract for 2015 and beyond. After launch the four small solar panels, high-gain antenna, and laser ranging instrument will be deployed.

Following a 7-month cruise, when the spacecraft arrives at Mars, a propulsive maneuver will place it into a highly elliptical orbit about Mars. This will be followed by a maneuver at apoapsis to raise the periapsis and match the plane of Phobos' orbit, and then a maneuver at peripasis to match the Phobos orbit period. Phobos will be observed from orbit for one month with a simple camera to improve the Phobos ephemeris and identify a specific landing location. Landing on Phobos will be done semi-autonomously using an altimeter and a feature detection camera similar to those used on the NEAR spacecraft.

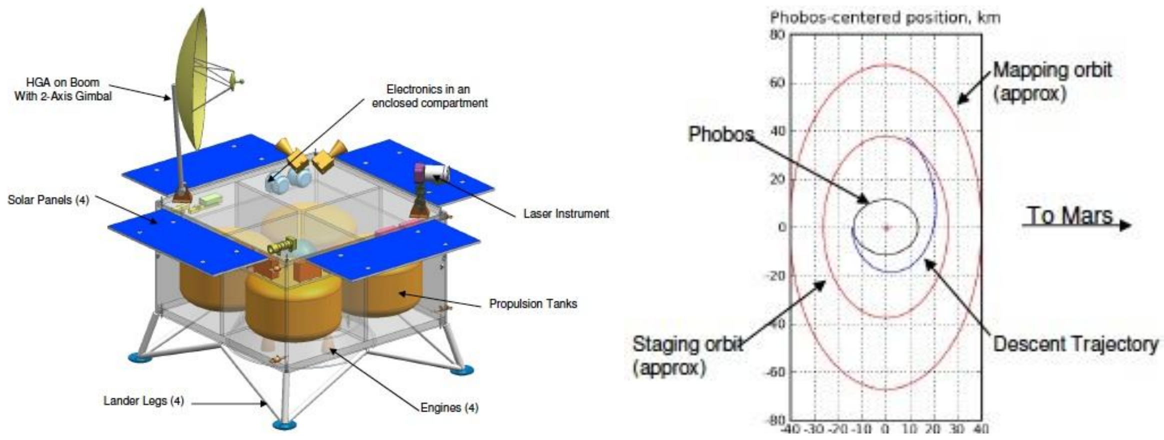

Figure 2. (a) PLR spacecraft in deployed configuration. (b) Phobos landing trajectory concept.

After landing, the spacecraft will have approximately three sun and Earth view periods of >3 hours, giving more than 5 hours with elevations >45˚ every Earth day. One of these view periods each day will be used for the hour-long laser ranging experiments. Once each week a second sunlit period will be used to send the instrument data to Earth via the high-gain antenna. Nominal science operations would continue for 3 years, covering two solar conjunctions. Since there are no expendables (e.g. propellant) during science operations, further observations could occur in an extended mission phase.

2.2 Measurement Description

The gravity parameter estimation is based on monitoring the light-time between Earth and Phobos. Unlike lunar laser ranging which measures the round-trip light-time from Earth to the Moon and back, PLR will use a combination of one-way light-times with asynchronous operation of the laser (Degnan, 2002). The advantages of the asynchronous scheme include: 1) noise immunity: the remote station does not transmit pulses in response to numerous background photon detections; 2) stable laser performance: steady pulse generation results in thermally stable conditions; 3) multiple Earth stations can range to the remote unit simultaneously without placing conflicting demands on the remote transmitter. The Earth stations will measure the times at which laser pulses are directed toward Phobos and the times of received photons. Similarly, the laser ranging instrument on Phobos will measure times of pulses transmitted towards Earth and the times of received photons from Earth. Scattered light will be rejected to first order by using a known laser pulse rate and filtering the measured times to find those separated by the signal rate. Timing will be done to an accuracy of 50 ps per photon, averaging down to < 3 ps for a typical observation. For the Earth station, the timing accuracy must be kept over the round-trip light time of ~3000 s. The laser ranging instrument accuracy need only be good over the few minutes it takes to collect enough photons to produce one-millimeter statistics. The timing scheme is indicated in Fig. 3a.

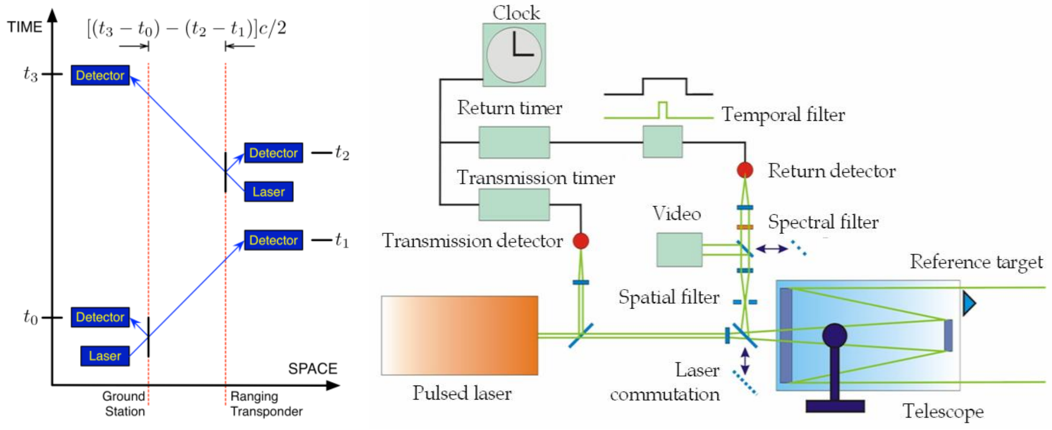

Figure 3. (a) Sequence of laser pulse time-tags used to derive Earth-Phobos round-trip light-time. (b) A block diagram of PLR and Earth instruments for timing transmitted & received pulse on common detector.

Both the Earth observatory and laser ranging instrument include a telescope and optics to have incoming light, and a small fraction of outgoing light, illuminate a photon sensitive detector array that records single photon arrivals (Fig. 3b). The power received by the telescope depends directly on the telescope's collecting area and inversely on the returning spot area. At the detector, both a pinhole restricting the field of view and a narrow-band-pass filter will be included to reduce background light.

Table 1. Signal and noise estimated for laser ranging from Earth to Phobos and back.

Input Parameters	Earth to Phobos	Phobos to Earth
wavelength (nm)	532	1064
transmit power (w)	3	0.25
tx efficiency	0.5	0.5
tx beam divergence (μrad)	25	160
tx pointing loss (dB)	-2	-2
tx atmospheric loss	-3	-3
tx pulse frequency (kHz)	1	1
rx atmospheric loss (dB)	-4.3	-4.3
rx diameter (m)	0.1	1
rx efficiency	0.3	0.3
rx field of view (μrad)	240	20
rx detector efficiency	0.4	0.4
background (W/m/m/sr/μm)	32	32
scattered light radiance (W/m/m/sr	100	100
Earth sky radiance (W/m/m/sr/μm	0	1000
bandpass FWHM (nm)	0.2	0.2
range(AU)	2.6	2.6
Derived Parameters		
photon energy (aJ)	0.37	0.18
space loss (dB)	-166	-162
rx signal power (aW)	9.3	1.9
planet background power (pW)	0.05	2
scattered light power (W)	0.15	6.9
sky radiance power (pW)	0	69
timing window (μs)	1024	27
Summary Results		
incident signal power (aW)	2.8	5.70E-01
incident noise power (pW)	2.7	21.3
SNR (dB)	-60	-76
detected signal rate (Hz)	3	1.2
detected noise rate (MHz)	3	46
timing window (ns)	10	10
data volume (MB/day)	100	1570

If the combined timing uncertainty per photon is 50 ps (from laser pulse width, detector response, timing electronics, clock), then one needs $(50/3.3)^2 = 225$ photon events in order to establish the one-way distance to 1 mm (3.3 ps) precision. At the estimated worst-case rates, this is achieved in a few minutes of ranging. However, it is assumed that all other parameters (beam pointing, divergence) are satisfied, which will not be true all of the time, so hour-long tracking passes are used to ensure that enough valid measurements are obtained.

The laser ranging instrument on Phobos will transmit pulses at a wavelength of 1064-nm for greater power efficiency and lower atmospheric scattered light at the Earth receiver during near sun pointing operations. A laser pulse rate of 1 kHz will be used with 12 ps pulse-widths and power of 0.25 W. We selected a divergence of 160 μrad to cover the entire Earth at distances greater than 1 AU At closer ranges, the instrument must point to a specific area on the Earth. For a 1 m aperture on the Earth station at maximum Earth-Mars range, the average detection rate will be 1.2 photons per second.

Transmission from the Earth station will be at a wavelength of 532 nm and detected by the instrument on Phobos with an efficient, low noise silicon-based single photon detector. The beam transmitted from Earth will have an uplink divergence of 25 μrad to cover potential pointing and atmospheric seeing variations. Assuming a laser power of 3 W (3 mJ/pulse at 1 kHz repetition rate) and a 12 cm aperture on Phobos, the uplink will deliver 3 detected-photon/second at the maximum Earth-Mars range.

The background event rates—due to scattered sunlight, illuminated body in field-of-view, and the radiance of the Earth atmosphere—will be much greater than signal event rates. At Phobos the laser ranging instrument will search for pulses in a 1 kHz repeat pattern following the tracking passes, and select only pulses within a narrow window about the times of the expected pulses from Earth for transmission. At Earth, the photon timings will be matched against predicted pulse rate and Phobos-Earth range to select correct pulses. Table 1 summarizes the worst-case measurement signal and noise estimates (note, “tx” and “rx” in Table 1 stand for transmit and received).

2.3 Flight System

The PLR spacecraft includes all equipment necessary to deliver and support the laser ranging instrument on Phobos. The spacecraft structure is a simple box-like construction to accommodate the payload, spacecraft electronics, propulsion, attitude control, telecommunications, thermal, and power subsystems. The mass by subsystem is given by Table 2. There are several operating modes, a typical power by subsystem is also given in Table 2. With the Atlas V 401 as the launch vehicle, mass and volume capabilities are much greater than necessary, so subsystems have been optimized to minimize cost rather than mass. Selected redundancy has been included in subsystem design to reduce risk where cost effective.

The command and data handling subsystem is based on the architecture being developed for the Mars Science Laboratory (MSL). It includes RAD750 processors, interfaces to the attitude control, telecommunication, power, and payload subsystems, with sufficient memory storage to accumulate up to two weeks of instrument data.

The power subsystem includes 5.3 m^2 solar panels and batteries to operate in absence of sunlight. The battery size is dictated by the propulsion system operation during Mars orbit insertion.

Table 2. Flight System Mass and Power Estimates.

Subsystem	Mass (kg)	Power Peak (W)	Peak Power Mode
Laser Ranging Instrument	39.3	50	Science
Attitude Control	29.4	48	Landing
Command and Data	22.0	47	Science
Power	71.4	71	Orbit Insertion
Propulsion	170.6	217	Orbit Insertion
Structure/Mechanisms	203.6	0	
Launch Adaptor	14.8	0	
Cabling	40.4	0	
Telecom	21.0	64	Data Transmit
Thermal	38.4	165	Cruise
Spacecraft Total (dry)	650.9	619	Orbit Insertion
Contingency	280.1	266	
Spacecraft + Contingency	931.0	885	
Propellant	1216.2		
Spacecraft Total (wet)	2147.2		

Thermal control will be done using standard multi-layer insulation and heaters. Spacecraft and electronics will be located in a thermally isolated box that will be kept warm during dark periods on Phobos. The propellant tanks will be kept warm until landing, and uncontrolled afterwards.

Telecommunications will utilize standard X-band transponders and traveling-wave tube amplifiers with a deployed pointable high-gain antenna 1.5-m diameter for sending instrument data to Earth, and two low-gain antennas used for contacts during cruise.

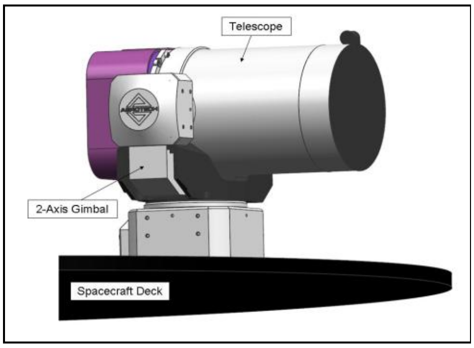

Figure 4. CAD model of laser ranging instrument telescope.

2.4 Payload

The instrument design is evolved from optical communications terminals under development for interplanetary missions. Prototypes of the communications terminals have been tested in airplanes. For the Phobos laser ranging science objectives, lower pulse rates are acceptable but higher timing resolution is required. The PLR instrument design is based on existing laboratory lasers and array photo-detectors which will be ruggedized to operate in space. The instrument is shown in Fig. 4 and a functional block diagram shown in Fig. 5.

The instrument consists of a gimbaled 12 cm telescope, a 250 mW Nd:YAG laser operating at 1064 nm, a silicon Geiger-mode (GM) avalanche photodiode detector (APD) array in 8x8 format, a multiplexed ASIC timing system to go with the detector, a clock, and an acquisition/pointing CCD camera with thermo-electric cooler. A small actuated mirror will impart a point-ahead angle to the beam with respect to the receiver direction of up to 330 µrad, which will be monitored via the centroid of a sample of the transmit beam imaged onto the CCD. A small fraction of the outgoing laser light will be reflected back from a reference mirror to the single-photon detector array for timing transmitted pulses. The laser will derive from a SESAM (Semiconductor Saturable Absorber Mirror) fiber seed laser, delivering 12 ps pulses at a 50 MHz repetition rate, followed by a pulse-picker that will accept only every 50,000th pulse to form a 1 kHz train. A laser diode-pumped regenerative amplifier will then deposit ~250 µJ of energy into each pulse for transmission to Earth.

The instrument electronics includes timing, pointing control, data storage, and a data post-processor. After acquiring photon times for the one hour tracking pass, the post-processor will look for the 1 kHz transmit pulse pattern from Earth and delete times outside a 10 ns window about that estimated rate, and format times into differences for reducing data volume. Edited times will be collected for transmission to Earth via radio, with a data volume of 5 MB per day.

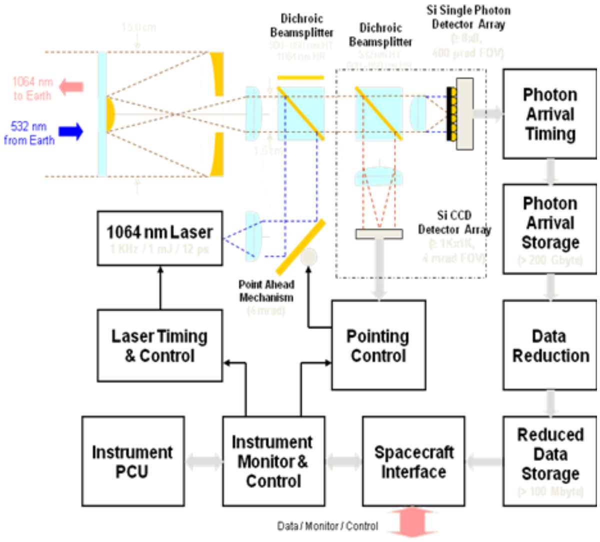

Figure 5. Instrument block diagram.

2.5 Ground Segment

One or more Earth observatories will be equipped similar to current lunar laser ranging stations and outfitted with membrane-type sunlight rejection filters for accurate measurements when Mars is near solar conjunction. The ground stations will use lasers very similar to those on Phobos, with the exception that the frequency will be doubled and the pulse repetition rate will be continuously tunable so that the pulse arrival rate at Phobos is exactly 1 kHz. The detector used in the ground stations will be an InGaAsP hybrid photodiode with a thinned photocathode to reduce timing jitter to less than 40 ps. A solar rejection filter with passband at 532 and 1064 nm must cover the entire ~1 m aperture of the telescope, which is a demanding task but one that has been previously demonstrated.

2.6 Mission Operations

Science operations will be done for one-hour tracking passes each Earth day. The spacecraft will have three view periods each day to select for operations. The tracking pass time will be selected to accommodate a view of the selected ground observatory for that day. Times will be optimized to have the observatory view Phobos at a high elevation, and sample the Phobos orbit by varying the time to alternate between before and after maximum elevation at the spacecraft. Times will be selected one week in advance. Once per week the spacecraft will communicate with the NASA’s Deep Space Network to download the previous week of science data and to upload the schedule of tracking times for the next week.

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